Jet Aircraft Propulsion

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Lecture No. # 39
Flow in Diffusers, Combustors and Nozzles

Hello and welcome to lecture number thirty nine of this lecture series on introduction to well jet propulsion. So, in this lecture series on jet aircraft propulsion, we have had quite some interesting discussion on different components of jet aircraft engine before that of course. We also discussed about the cycle analysis both the ideal cycle as well as the real cycle analysis of jet engines, subsequently we also got an opportunity to talk in depth about different components which constitute a jet engine starting from the intake the fan compressor combustion chamber the turbines and of course, the nozzles. We have seen different types of these components like different types of intakes; different types of compressors; this axial and the centrifugal compressor, the combustors, the turbines and also the different classifications of nozzles.

So, after having discussed these different components these individual components in detail we also started some discussion on matching of the components subsequently we have had some discussion in the last few lectures on ramjets and pulsejets. So, I think I have mentioned several times that ramjets are very simple types of engines and In fact, pulsejets are also very simple engines in the sense that both these engines do not really have the rotating components which are characteristic of the traditional or conventional jet engines like turbojets or turbofans and so on…

So, the absence of these rotating machinery makes the whole engine at least conceptually very simple, but So you may wonder if they are very simple why is that they are not used and why do we have to really use these complicated machinery in actual practice. Well, the practical limitations of using these engine concepts and for example, ramjets cannot generals and lot of other physical features which have been provided to ensure stability.

Ramjet combustors have flames stabilizers or flame holders which will ensure that the fate any static thrust. So, if you were to use ramjets on an aircraft the aircraft cannot takeoff because ramjets cannot generate any static thrust and ramjets are more efficient, only in supersonic mach numbers.

So, unless of course, we come up with a concept of using both these engines together that is let us say conventional turbojet engine, which will takeoff and accelerate to the supersonic mach number subsequently, the ramjets can take over. There are some of these concepts, which I think we will discuss in the next class which will be our last class on last lecture, on this lecture series. So, some of these advance concepts which involve integration of the traditional jet engines with some of the more advanced jet engines like the ramjets will be disused in little bit detail in the next lecture. In today's lecture, we are going to discuss about the ramjets; the components of ramjets and how do we take a look at in detail what are the different constituents of a ramjet and how can we analyze ramjets and so on...

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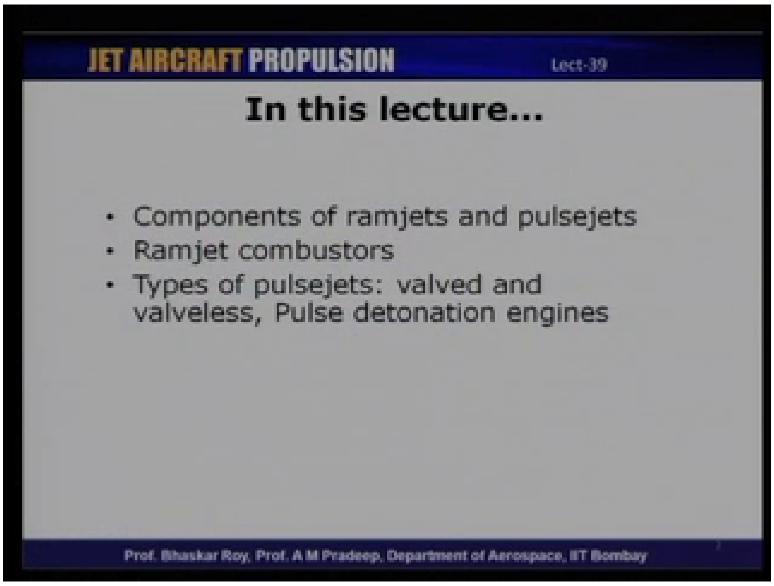

In today's lecture let us take a look at: what are the topics that we are going to discuss. So, we are going to talk about the components of ramjets and pulse jets. We will also be talking about ramjet combustors in little bit detail, which we will see very soon that they are very similar to the after burners that you might have discussed during the turbojet engines. So, ramjet combustors will be taken up in some detail, we will also see how we can analyze ramjet combustors and determine total pressure loss across combustors and so on… we will subsequently take up the different types of pulsejets engines, the valve and valve less pulsejet engines. We will also be talking about in very brief about a conceptual cycle based on pulsejets which are known as the pulse detonation engines.

So, these are some of the topics that we are going to take up for discussion in today's lecture. We are going to have primarily an over view of the different components and we are not going to analyze some of them in detail, because we have already done. For example, an air intake that we have discussed in very much detail in some of our earlier lectures similarly, nozzles we have discussed in detail. So, we are not going to revisit these concepts and these topics all over again. we are going to assume that you have already understood the working of air intakes and nozzles because it is a same concept which is used here as well.

But combustors, we will see in little bit detail on how we can analyze combustors how we can calculate pressure loss and temperature raise in combustors etcetera. So, let us begin with ramjets and as I have mentioned ramjets are probably one of the simplest forms of jet engines, which are which have been evolved; which have worked. In fact, the Germans had used ramjets very extensively during the second world war and some of their advanced military aircraft had the ramjet based propulsion system and there were very successful and had created lot of problems for the allied forces to resist the power of some of these advance types of engines, which were un known to the rest of the world at that time.

Ramjets has been used for a long time ,but they will not really been used for civil aviation. In fact, you the majority of application of ramjets has. So, far been limited to military application they are still used primarily for missile propulsion. So, many of the missiles which have to have longer range will benefit by using an engine like a ramjet, because ramjets are air breathing propulsion system which means that a missile which uses ramjet engines does not have to carry an oxidizer it just has to carry fuel and since ramjets are air breathing that will improve or increase the range of such missiles and some of the long range missiles, actually use ramjet engines.

Of course the initial part of the missile will still have a booster phase which will be a rocket propellant or rocket engine which could be either solid propellant or a liquid propellant, which will take the missile to a certain Mach number from which the ramjets can begin to operate. So, they have been used and they are still used in many of the modern day missiles, but they have not really been used in aircraft application or at least now. But some of the earlier generation aircraft, which had supersonic curse, used ramjet engines, but they are not used anymore and they have definitely not been used in civil aviation. Ramjets being very simple in the term at least conceptually very simple to design. So, besides the fact that ramjets do not have rotating machinery makes the design of ramjets even simpler and that is the reason why ramjets still have lot of potential in terms of their application to civil or military aviation.

So, let us take a look at: a few salient features of ramjets before we go on to the components of a ramjet. So, in a ramjet there are basically three components as we know ramjets consists of intake they consist of combustion chamber and the nozzle. So, how does a ramjet work? We have seen that little bit detail in the last class in a ramjet. The compression process is taken care of purely by the intake, because ramjets as we know as even the name suggests depend basically upon the ram compression of air, that is as the engine is moving at very high speed the incoming air is decelerated from very high Mach number to very low Mach number; subsonic Mach numbers and in that process there is a substantial increase in pressure.

That is a basic principle behind compression of air incoming, air just within the intake. So, intake of a ramjet not only surf the purpose of an intake as such they also take care of the compression as such so, the entire compression process is handled by the intake downstream of the intake. We have a combustion chamber, combustion chamber as we will see very soon is very similar to that of after burner and these combustion chambers have certain flame holding devices to ensure that the flame is held stable within the combustion chamber and it does not really move out and downstream of the combustion chamber. We have the nozzle, which accelerates the combustion products through the through them resulting in a thrust; which is a generated and that is what propels the ramjet forward.

So, with the use of just three simple components ramjets are able to generate thrust; ramjets have a over the years been demonstrated to be very successful, but there are lot of disadvantages, which we have been discussing the main disadvantage being the fact that ramjets cannot generate static thrust.

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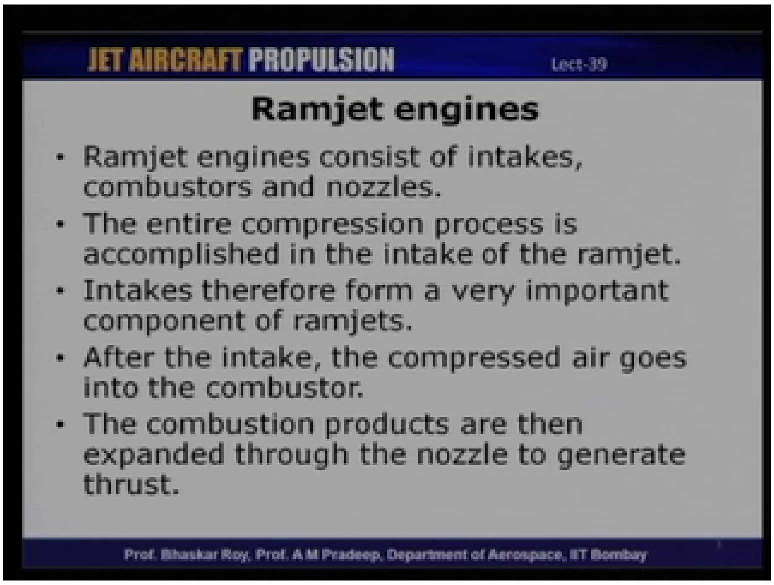

So, in a ramjet engine the intakes. In fact, all the three components are important where the intake will play a little more important in a ramjet, because they have to take care of not just the capturing air from the free stream intakes also need to carry out the compression process. So, intakes form a very important component of ramjets and after the intake as we have discussed the compressed air from the intake goes into the combustor and combustion products are expanded through the nozzle to generate thrust.

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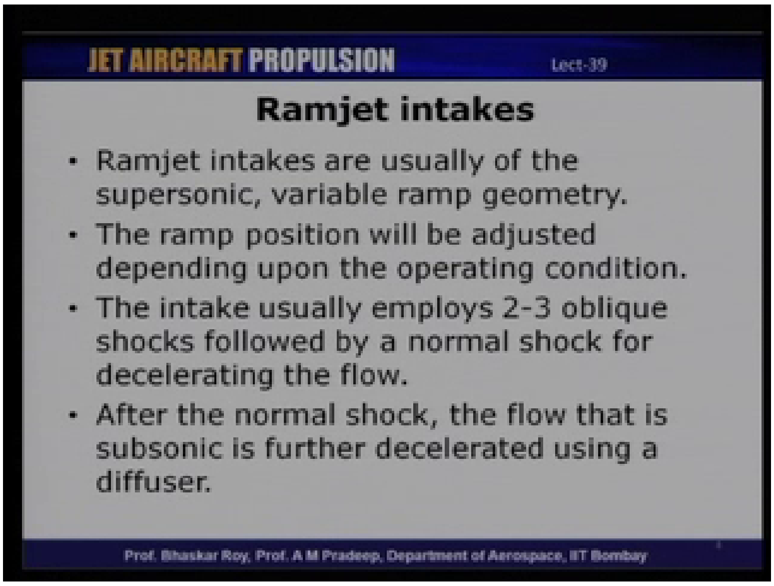

So, let us a look at these components one by one: ram intakes, we will not discuss in too much detail, because these intakes are very similar to the supersonic intakes that we have discussed in detail long back. Supersonic intakes as we have seen will basically consist of a conversion, diversion section wherein the flow is first take to a section where the area is decreasing and convergent and the area becomes minimum at what is known as the throat and downstream of the throat, we have an increasing area. We have seen that the intake operation is very sensitive to the inlet and exit conditions, which means that if we have a fixed intake then it operates efficiently only for its design condition.

And under off design conditions the intake performance can be crossly suboptimal and therefore, these intakes have to necessary that these intakes have certain variable geometry features incorporated in them. So, that when the aircraft is operating under off design conditions the intakes can still deliver thrust which is a thrust and other performance parameters which are not very far from the optimal. Typical ramjets ramjet intakes will have a spic or a center body, which can be adjusted to adjust the location of the shocks. So, a ramjet as we have seen is more efficient when it operates at supersonic mach numbers, which means that the deceleration in the intake occurs through shock waves. We have seen different types of intakes; we have seen external compression, mixed compression, internal compression intakes and fixed and variable geometry.

So, most of the ramjets that that have flown so far have excess symmetric geometry they do not really have a 2D geometry, because the whole engine is very simple, if it is 2D then that 2D geometry has to be really converted to circular in the combustion chamber and then again the nozzle. So, normally the ramjets that have been demonstrated over the years have an x symmetric geometry and. So, the intake center body is also an x symmetric spic which can be adjusted. So, as to locate the shocks according to our desired positions and usually the intakes ram will have or generate two or three oblique shocks eventually, ending in a normal shock because in a ramjet the combustion can take place while combustion takes place in subsonic speeds.

So, a supersonic Mach number flow has to be decelerated using these shocks and then it becomes subsonic before it enters the combustion chamber. So, through these shocks of course, there is there are stagnation pressure losses, which are incurred and we have seen that but these can be controlled or kept minimal by ensuring that there are enough number of oblique shocks before a normal shock. So, we may not want to really use a single normal shock to decelerate a supersonic mach number to a subsonic mach number because that incurs a lot of stagnation pressure loss, which will eventually result in thrust loss. So, a use of a few oblique shocks two to three are the ones which are commonly used two or three oblique shocks followed by a normal shock that would be a kind of a an optimum configuration for a typical ramjet intake.

So, after the normal shock of a ramjet intake then the intake then progresses and becomes a purely subsonic diffuser, because after the normal shock the flow is subsonic. So, then downstream of the normal shock we have a diverging area, diverging area in a subsonic flow leads to deceleration. So, the flow is further decelerated from high subsonic to low subsonic before the flow enters the combustion chamber, because in the combustion chamber we would like to have relatively lower velocities. So, that there is enough time for the fuel to burn within the length of the combustion chamber because if we have a flow which is coming at a very high speed there are two issues. Firstly, it may lead to stability issues there are the flame may not be stable in the combustion chamber and the other thing is that that would also necessitate a larger length of the combustion chamber.

So, that the fuel has enough time to ignite and burn within the combustion chamber so these are to be avoided. We would like to decelerate the flow to relatively low velocity before the flow enters the combustion chamber. So, these are the different functions of the intake we have already discussed in take in lot more detail earlier. So, I will not go into the details of that all over again. But let us look at the next component which is the combustor we have already seen and discussed about combustors the main combustors of jet engines and there we have seen there are different types of combustors the can type the can-annular and cannular type and so on…

So, in a ramjet combustor the main combustor is different, ramjet combustor is very different from that of the main combustor of a jet engine, but the ramjet combustor can be very similar to an after burner. we have also seen some after burner geometries earlier on. So, ramjet combustor has some similarities with an after burning or an after burner of let us say a turbojet engine and. So, we will discuss about some o the components or details of a ramjet a typical ramjet combustor.

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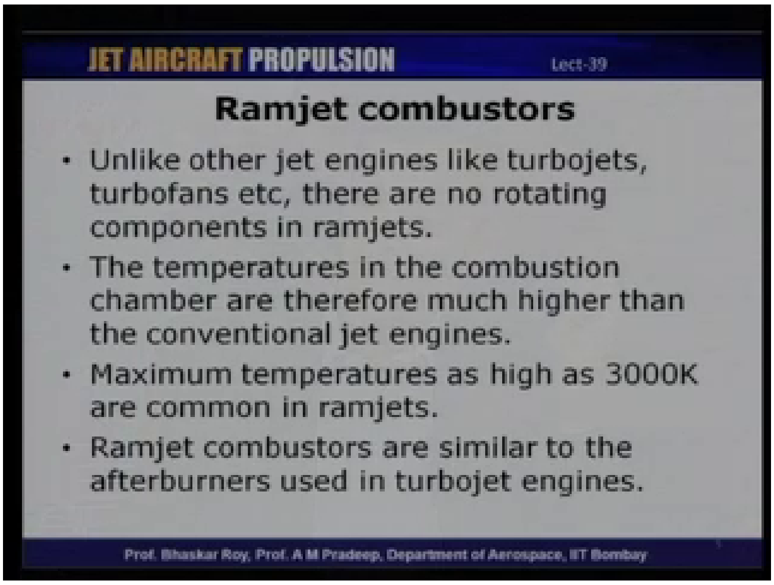

So, unlike in turbojets where there are rotating components ramjets do not have any rotating components. So, that is a big advantage for a ramjet because we can now afford to have temperatures which are much higher than what were used in conventional jet engines. So, there are maximum temperatures as high of 3000 Kelvin or have been commonly used in ramjets which are unthinkable for conventional jet engines, because there are limitations by the turbine blade which limits the temperature to about 1500 hundred or 1600 Kelvin and not beyond that, where as in ramjets we can use temperatures as high as 3000 Kelvin which is a substantially higher temperature.

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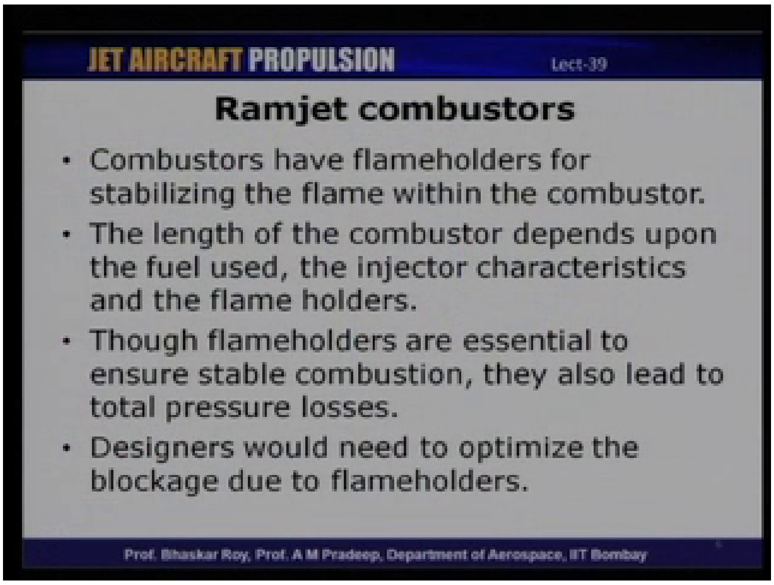

Ramjet combustors, as I mentioned are very similar to the after burners, which are used in turbojet engines. Ramjet combustors are characterized by flame holders so; flame holders are basically devices or certain bluff bodies, which have been designed aerodynamically to ensure that the flame remains stable within the combustion chamber. Because flame stability is a very important issue unlike in traditional or conventional combustion chambers, where there are liners and other things which can take care of stability plus there are swallows and lot of other physical features which have been provided to ensure stability.

Ramjet combustors have flames stabilizers or flame holders, which will ensure that the flame remains stable and that the combustion can be a completed within the length of the combustion chamber itself and that is a very important which will constitute a typical ramjet combustor, but of course, the presence of these flame holders may also lead to stagnation pressure loss. So, the designers of combustors would need to keep in mind although we would like to have a larger surface area of these flame holders for better flame stability increase in surface area can; obviously, lead to increase in stagnation pressure loss.

So, there is an optimization problem there where one would like to keep the flame stability limits as high as possible. At the same time you would also like to ensure that the stagnation pressure losses are kept minimal, because stagnation pressure loss in the combustion chamber will lead to thrust loss eventually it will all affect the thrust. So, designers would need to carry out an optimization to ensure that the flame stabilizers or flame holders not only give a fairly reasonable stability margin, it also ensures the pressure loss stagnation pressure losses have kept minimal.

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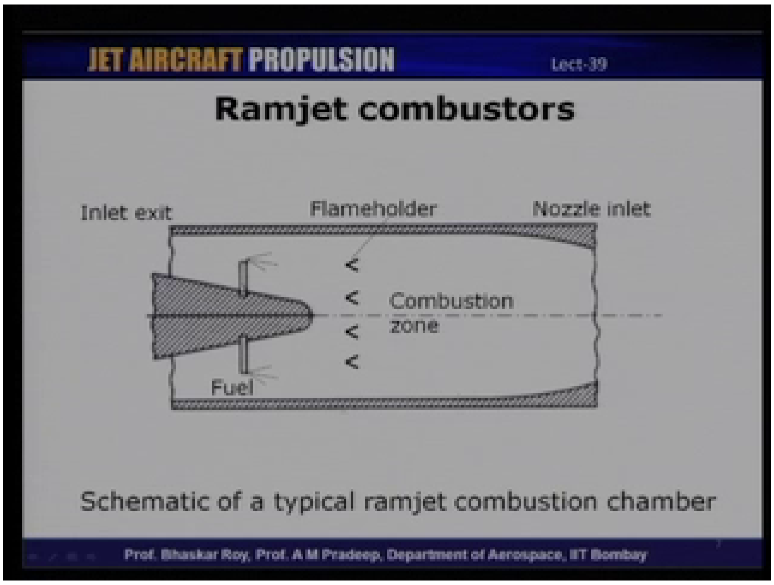

So, that is one of the things that the designer would like to keep in mind. So, this is a typical schematic of a ramjet combustor as you might have seen it is very similar to that of an after burner now in this schematic let me explain what this is all about. So, here we have the intake or an intake exit. So, the air which is coming in from the intake, exits at this point. So, this is probably the exit of the intake and somewhere on the center body one might want to keep the fuel injectors. So, fuel is injected through the center body here and then this entire length from here all the way up to the nozzle entry constitutes the combustion chamber and somewhere here we might have the flame holders, which I mentioned were are typically bluff bodies, which are aerodynamically designed and these flame holders ensure that the flame is restricted to the combustion zone.

So, the combustion region is somewhere here we will see the operation of the flame holder in little more detail latter on. So, the flame is held stable or tried to held, we tried to be stable within this combustion zone after the combustion region of course,, we have the nozzle where this is the nozzle entry. We have the convergent section then ending in a throat followed by a divergent section. This is a typical ramjet combustor and as you can see: here the intake exit also has a divergence section, because we are continuously decelerating the flow in a subsonic mach number a diverging area leads to deceleration.

So, that is how we accomplish deceleration by increasing the area fuel is injected here and it gets ignited because of the and the flame is held stable by the use of flame holders, which ensure that the flame is held stable within the combustion region itself.

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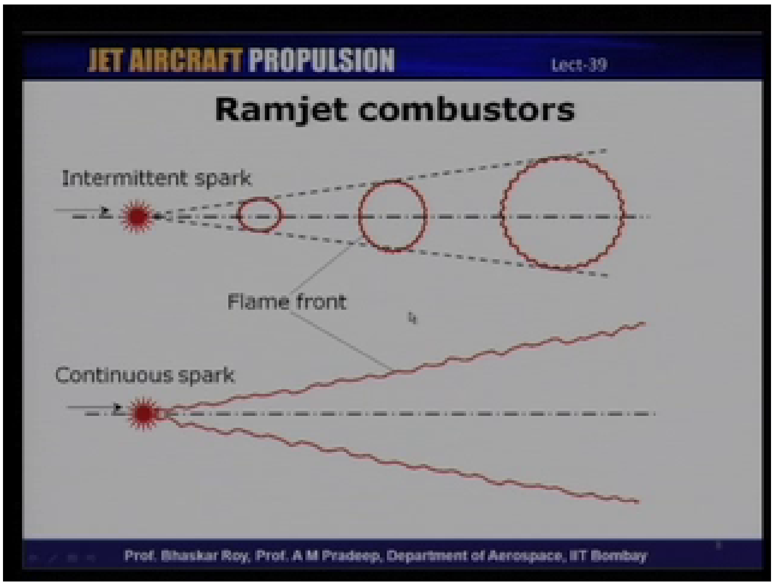

So, I mentioned about the flame stabilizers. Let us now look at: what is it that flame stabilizers basically do. So, understand the working of flame stabilizer let us consider two cases let us consider a case where there is a spark plug which is used to ignite an air and fuel mixture and on one hand we have an intermediate spark and let us say we also have a continuous spark. So, if we have an intermediate spark. So, every time the spark is initiated there is a combustion which gets started. So, the combustion products, which are indicated or the flame front indicated by these wave v red circles we will propagate downstream because there is a certain speed to associate velocity, associated with the incoming mixture air and fuel mixture and as the spark is ignite or the spark is started. It ignites the air fuel mixture and the flame front as you can see here propagates radially outward and as it moves downstream the flame front gets larger and larger.

So, this is how a flame front would propagate if we have an intermediate spark. On the other hand, if we have a continuous spark then there are infinite numbers of these flame fronts which are generated. So, we what we see will be flame front, which looks like this we see a continuous flame front because there is a continuous spark which ignites and causes the flame front to propagate radially outward. So, since there are infinite number of these we do not really see individual flame fronts as we see here, which is on account of the intermediate nature of this spark. Here, we have a continuous spark which ensures that the flame front also is continuous. In a ramjet one would like to have a flame front, which is very similar to that of a continuous spark. we do not really want a intermediate spark we would like to initiate combustion using a spark plug let us say ,but once ignited the flame should be self sustained.

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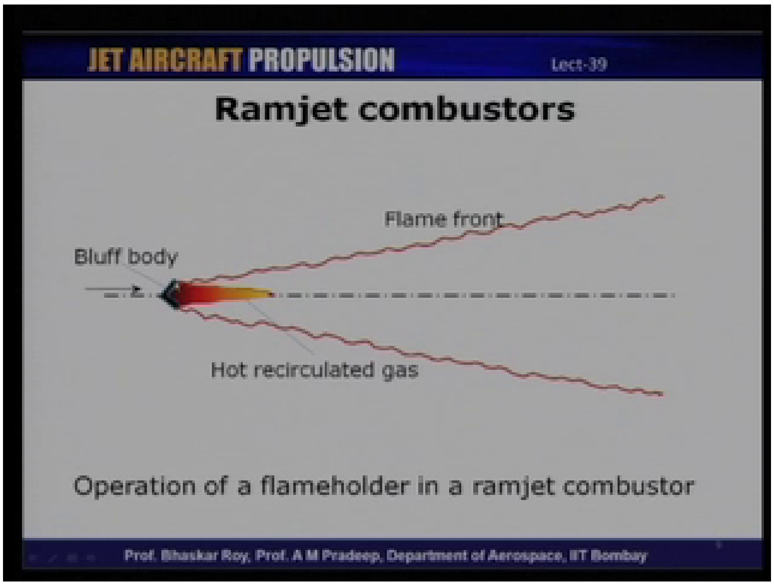

So, in a ramjet combustor what we do is that we provide a bluff body. So, we will see here the bluff body which is what which is very similar to the bluff body I had shown for the ramjet combustors. So, let us go back there.

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So, these are the flame holders as we cans see. So, downstream of this what happens is what we are taking a look at?

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So, this is the flame holder at typical flame holder a bluff body and those for whom are undergone courses on aerodynamics would immediately realize that since this is the bluff body downstream of the bluff body should be a wake is the region where there is a vertex where they have numerous vertices the high wale is characterized by high levels of turbulence and recirculating flow.

So, downstream of the vertex downstream of the bluff body, we have a vertex dominated recirculating flow and. So, here we have the flame we air and fuel mixture coming in and let us say once the flame is ignited using some means by a spark plug say. Once the flame is ignited the flame front will propagate as shown here because of the fact that once you ignite downstream of the bluff body we have a lower velocity much lower velocity flow and there is recirculation hot recirculation of the gas. As a result of this the bluff bodies then itself or the recirculated region behind the bluff body will itself act like a continuous spark.

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So, in a continuous spark we have seen that the flame front we will assume a shape like what you see here because the infinite number of flame fronts which are present. So, the presence of the bluff body and the consequent as a consequence of that the hot recirculated gas downstream of the bluff body cause generation of these flame fronts which will ensure that the flame is held stable and within the limits of the combustion chamber. So, this is how a typical flame holder is going to work that is downstream of the bluff body of the flame holder we have hot recirculated gas which will ensure that the flame fronts are held or a kept in a stationary or stable mode to ensure that the flame is held stable within the limits of the combustion chamber.

So, a flame front is, the presence of a flame holder is essential for ensuring that we have a stable combustion within a ramjet combustor. So, in a typical after burner also you would have a flam stabilizer or a flame holder very similar to what we have discussed. So, the presence of flame holder ensures that the flame is held stable within the combustion chamber. So, what we are going to do next is to analyze typical combustion chamber in a very simple manner. We will carry out a one dimensional analysis of flow through a combustion chamber carryout momentum balance and see how we can calculate or estimate the pressure loss stagnation pressure loss in the combustion chamber as well as the change in stagnation temperature across the combustion chamber.

So, we will use a very simple 1D model to calculate the pressure loss as well as the stagnation temperature rise in a combustion chamber. So, what we will see is that even if there are no frictional losses there will still be a certain amount of pressure loss, because of the fact that we are adding heat in a constant area duct. So, those of you who would have a studied rally flow which is basically or basically flow through constant area duct with heat transfer we will understand the fact that there will be a pressure loss associated with heat addition in a constant area duct and this is not because of the fact that there is a friction even, if we assume a no frictional losses there will still be a certain amount of total pressure loss which comes into picture.

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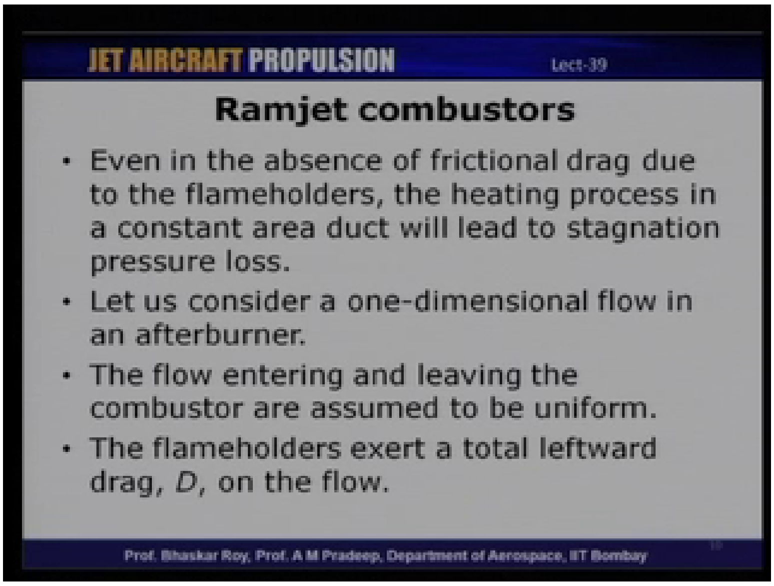

So, we are going to analyze a flow where we will calculate the total pressure loss not just because of friction. Friction also it will assume there is something present ,but even otherwise we will see that even if the frictional losses are zero they will still be a certain amount of pressure loss. So, to analyze that we will consider 1D flow in after burner or a or a combustor we will; obviously, assume that the flow entering and living the combustor are uniform and that the flame holders will exert a certain drag which we will denote by D on the flow. So, this drag is a towards the left hand side as we will see little latter.

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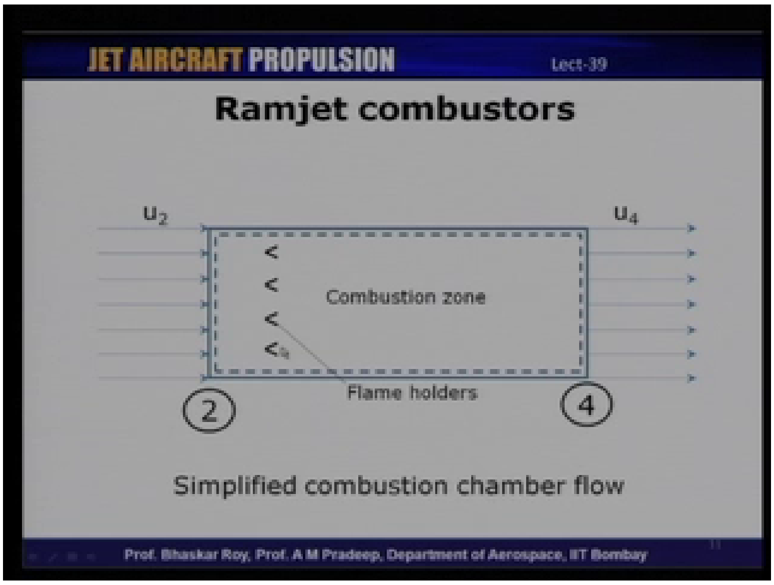

So, this is the simplistic combustor model that we are talking about U 2 refers station 2 refers to the inlet of the combustor station four refers to the exit of the combustor. So, let us say u two is the flow axial velocity entering combustor and U 4 is the axial velocity living the combustor and within the combustor zone, which is indicated by these dotted lines. We have these flame holders as well, this is a very simplified model of a combustion chamber flow and we are going to analyze the flow that is that is basically applicable for this kind of a very simple 1 D combustion flow.

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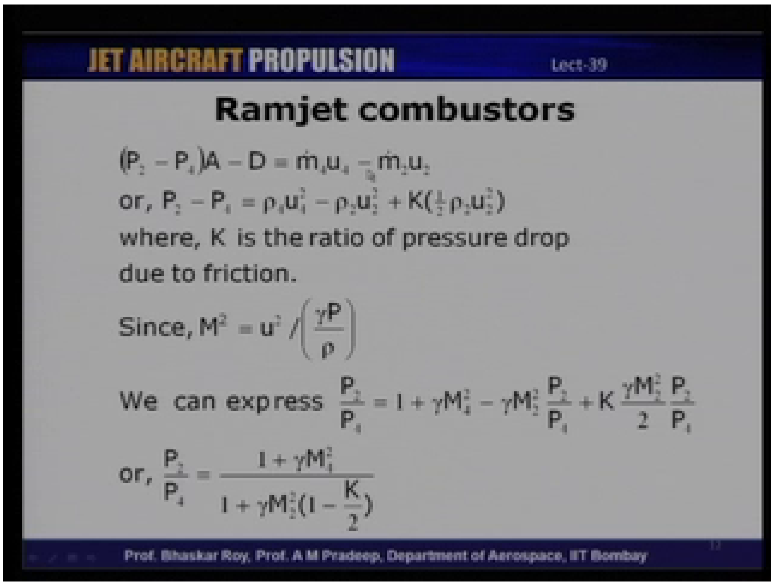

So, flow through this we will as I had said the flame holders exert a certain drag, which is towards the left hand side and therefore, we denote it by the parameter D, which is basically drag difference in static pressure at the inlet and the exit is possible and therefore, there is a corresponding force associated with that and that is denoted by P 2 minus P 4 multiplied by the cross sectional area. So, this is the net change in momentum or the force, which is basically the difference in the momentum of the flow between the exit and the out inlet. So, exit momentum is basically mass flow rate at the outlet multiplied by the corresponding velocity similarly, the mass flow rate at the inlet multiplied by the corresponding velocity.

So, of course, mass flow rate at the inlet and outlet are more or less same except for the fact that M dot 4 also includes certain amount of fuel which is added in the combustion chamber. So, this we can simplify now when we simplify that we get P 2 minus P 4 is rho 4 use u 4 square minus rho 2 U 2 square. Basically because mass flow rate is rho into a into U. So, as is common factor here. So, which gets cancelled out and therefore, mass flow rate becomes rho times u four multiplied by U 4. So, U rho U square minus rho 2 U 2 square plus K time's half rho 2, U 2 square here K is assumed to be the pressure drop due to friction. So, that also I found for the drag which has been accounted for in this parameter K.

Now, we shall now express this in terms of mach number some mach number we know is M square which is basically the ratio of velocity square to speed of sound which is square root of gamma r T which is gamma P by rho. So, we express this equation that we have written P 2 by P 4 as 1 plus, we have expressed all these all these velocities ratio of density and velocity square in the form of Mach number.

So, we have P 2 by P 4 is one plus gamma M 4 square minus gamma M 2 square into P 2 by P 4 plus K times gamma M 2 square by 2 into P 2 by P 4. So, this is simplifying this equation that we have written here we have simplified that in the form of P 2 by P 4. So, basically we divide throughout by P 4 we get P 2 by P 4 minus 1 is equal to this and that is how we get one plus gamma M 4 square and so on...

So, this again can be simplified we have simplified that in the form of what is seen here, because we have P 2 by P 4 on both the sides. So, if we express that in the form of these static pressure ratio we have P 2 by P 4 is one plus gamma M 4 square divided by one plus gamma M 2 square into one minus K by 2 here K is the parameter which is associated with the pressure drop. So which means that even if K is zero, which means if there are no frictional losses being assumed there will be always a certain pressure difference, because of the fact that the Mach number is different as you add heat in a constant area duct.

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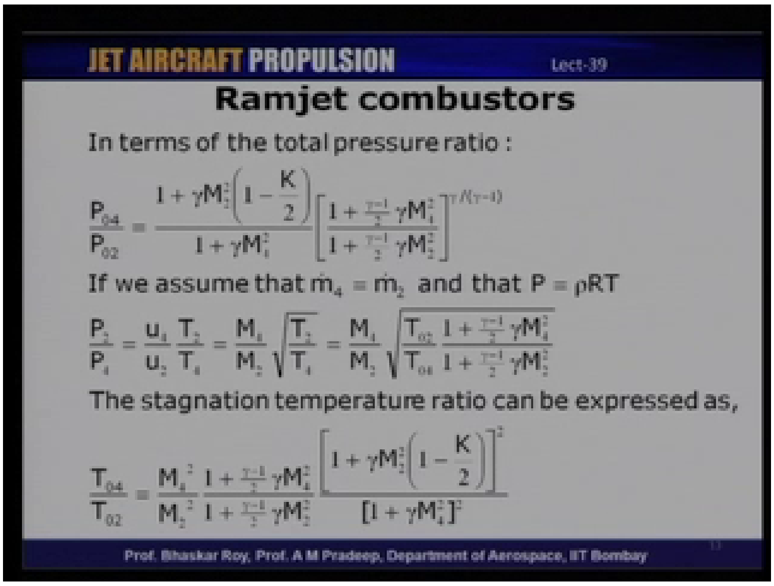

So, we will now proceed to express this static pressure ratio in the form of stagnation pressure ratio. So, P 2 by P 4 in terms of stagnation pressure ratio from the isentropic relations. So, the evolved equation which we can simplify we get one plus gamma M 2 square into one minus K by 2 divided by one plus gamma M 4 square this whole thing multiplied by one plus gamma minus one by two into gamma M 4 square divided by 1 plus gamma minus 1 by 2 into gamma M 2 square, whole raise to gamma by gamma minus 1. Here, we have expressed the total pressure ratio the previous equation was for static pressure ratio. We have now expressed that in terms of the total pressure ratio, if you assume that the fuel added is much less as compared to the mass flow rate of air itself. We have m dot 4 is equal to m, m dot 2 and from straight equation we have P is equal to rho R T then we can also express the static pressure ratio in the form of stagnation temperature ratios.

So, we have a P 2 by P 4 is u four by u two into T 2 by T 4, which is M 4 by M 2 square root of gamma square root of T 2 by T 4; which again we have expressed in terms of a the isentropic relation square root of T 0 2 by T 0 4 1 plus gamma minus 1 by2, M 4 square by 1, plus gamma minus 1 by 2 M 2 square. So, stagnation temperature ratio can therefore, be expressed because we have stagnation temperature ratio here we have simplified this equation we can express this stagnation temperature ratio T 0 4 by T 0 2 as 1 M 4 square by M 2 square into 1 plus gamma minus 1 by two M 4 square by 1 plus gamma minus 1 by 2 M 2 square this multiplied by M plus gamma M 2 square into 1 minus K by 2 this whole square divided by 1 plus gamma M 4 square the whole square.

So, we have now two equations we have which we have derived from fundamental one dimensional analysis of flow through combustors one of them is pertaining to the stagnation pressure drop across the combustion chamber and the other one pertaining to the stagnation temperature raise across the combustion chamber. Both these equation we have seen this a parameter K, which is denoting the pressure loss in the pressure loss as a result of or frictional losses associated with the presence of the effects of viscous forces or viscous x even if you assume K to be zero. we will still see that P 0 4 P 0 2 by P 0 4 and T 0 4 by T 0 2 still have a certain number associated with them, which means that there will still be a certain stagnation pressure loss occurring not just because of friction ,but because of the fact that we are adding energy or heat into a constant area duct and in the absence of friction also it leads to a certain pressure loss.

This one way, in which one can analyze flow through combustors in a very simple manner, based on certain parameters which can be calculated like Mach number at inlet and exit and the static pressures. Based on these parameters one can estimate and calculate this stagnation loss, which a combustor is likely to incur as a result of frictional losses as well. As a result of heat addition in a constant area duct. We have analyzed combustion chamber in a little bit detail so far and this combustion chamber analysis. As, we are seen it is primarily with a one-dimensional assumption, which is fairly reasonable because in a ramjet combustor. We have seen it is a much simpler combustion chamber as compared too. Let us say the main combustor of a jet engine a gas turbine engine, where the combustion chambers can be little more complicated.

A 1D analysis for such combustors may not really be true, where as ramjet combustors, 1D analysis can still be assumed to be reasonably good estimate of what is happening within the combustion chamber. We will now take a look at the next component that constitutes a ramjet which is the nozzle you already discussed nozzle in great detail in some of the earlier lectures we have seen there are different types of nozzles at convergent nozzle is used in subsonic flows a convergent divergent nozzle is what one would use in a supersonic flow. As, I said ramjets are primarily operational in supersonic flow ramjets would need to have a C D nozzle that is a convergent divergent nozzle.

The reason being that one would like to accelerate the flow to supersonic speeds most of the ramjets as I have said have an excess symmetric geometry. The nozzles also have an excess symmetric geometry with a provision to with or without provision to vary the area and. So, if a ramjet has to operate over a variety of range of operation in terms of Mach number and altitude then the use of variable area nozzle becomes significant, because if a ramjet is designed a nozzle is designed for a particular operating condition it may not be very optimal or efficient under off design conditions. To ensure that the ramjet, the nozzle operation is still fairly optimal or efficient at other of conditions other off design conditions, one would like to incorporate variable nozzle geometry some of the ramjets also have variable nozzle geometry incorporated in that.

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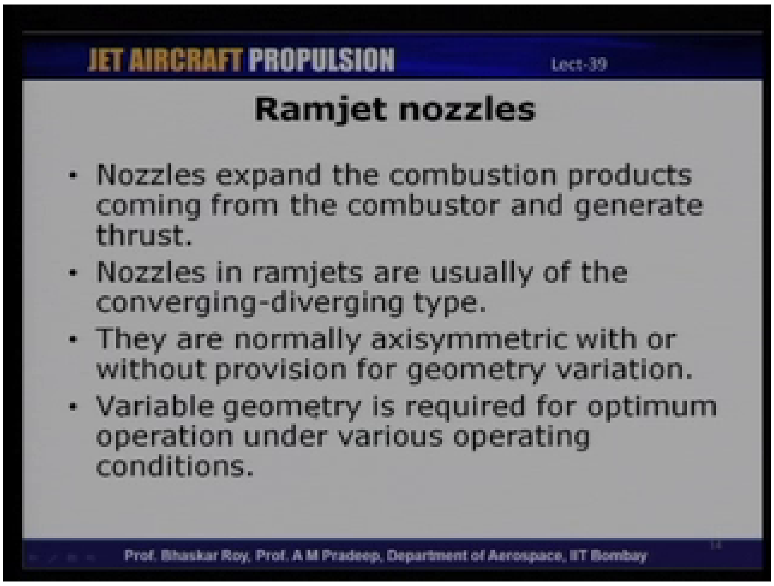

So, most of the nozzles as I said are excess symmetric and variable geometry is basically required for optimal operation under various operating conditions. So, we will not discuss more details of nozzles, because we have already discussed a one full chapter on nozzles; different types of nozzles. Now, there is another aspect of ramjet that ramjets can be of different types. So, far we have seen ramjets the once which we have discussed at least the schematic that I have shown in the last class was true for one type of a ramjet and there are several other variance or types of ramjets, which are which have been proposed some of them have been used and some of them continued to be on the conceptual level ,but seem to show promise.

So, let us see what are the different types of ramjets which are possible again we will not go into too much details of the geometries etcetera a because that is not really in the scope of a the syllabus of this course.

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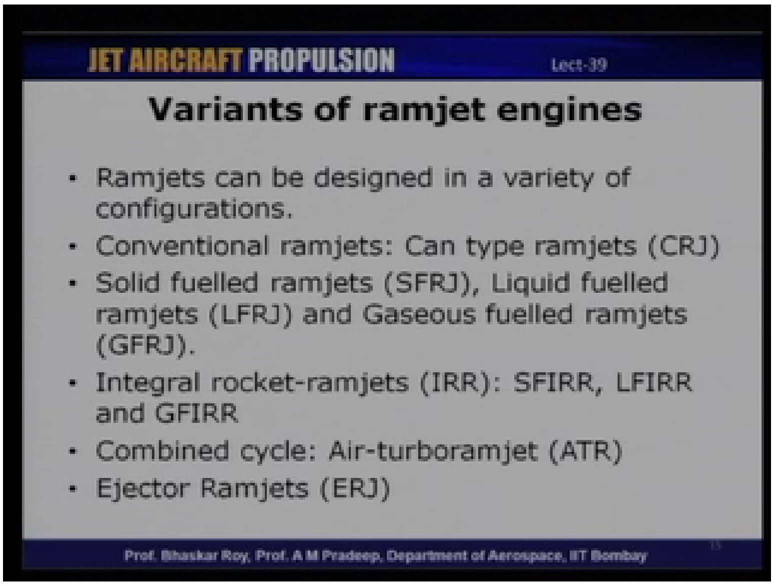

So, there is variance of ramjets and there are different types of configurations, which can be thought off. So, the conventional ramjets which are what we were discussing. So, far are sometimes refer to as can type ramjets, because their combustors are similar to the can type of a combustion chamber of a gas turbine engines. So, these are basically called can type ramjets sometimes denoted by C R J depending upon the fuel that is used in a ramjets. One could have either solid fuel ramjets, which are S F R J, or liquid fuel ramjets or gaseous fuel ramjets. So, either of all these three possibilities are there the liquid fuel ramjets being little more popular than the others.

Now, ramjets can be integrated with a rocket, because as I said ramjets cannot takeoff on their own, which means they need some assistance in taking off or reaching their starting speed and most often rockets are used for carrying the ramjet to the desired speed so such a ramjets are called integral rocket ramjets. Now, again depending upon the kind of fuel, which is used you may have a solid fuel integral rocket ramjet or liquid fuel integral ramjet or even a gaseous fuel integral ramjet.

It is also possible that one can combine a ramjet with one of the conventional engines; ramjets combine with let us say a turbojet engine. So, a turbojet will take off the aircraft take it to a certain desired speed before the ramjets can start operation. So, such engines which are combination of ramjets and conventional engines are called the combine cycle mode these are called the air turbo ramjet. I think in the next class in the last lecture we will see some more details of air turbo ramjets and what is meant by air turbo ramjets and how they operate and. So, on we will live those details for the next class.

There is also another class of ramjets engines, which are known as ejector type ramjet; where in ejector stream is used for propelling the ramjet forward. As, you can see there are different types of ramjets, which are possible we have only discussed one of them in detail that is the conventional ramjet or the can type ramjets and of course, there could be variants of these ramjets depending upon the cycle. They are operating and their function that these ramjets are required to operate upon.

So, this winds up our discussion on ramjets in some detail. Let us move on to pulse jets, we have also already discussed pulse jets and their cycle analysis. In the last class today we are going to discuss about different types of pulse jets and we will see what are the different features of these two different types of pulse jets now pulse jets as we have discussed in the last class are yet another class of simple or so, called simple jet engines and I call them simple because they do not require the use of very complicated turbo machinery like compressors and turbines.

Because presence of this rotating machinery makes the design extremely complicated and something that is very difficult to design and optimize and develop, where as ramjets and pulsejets where at least pulse jets for that matter are. So, simple that one can actually try and develop them in a laboratory scale and many of them have been actually demonstrated on a very amateurish lab scale unlike jet engines which cannot really be demonstrated on such a scale, which is why pulse jet engines are much simpler and even. In fact, simpler than a ramjet engine for that matter, there are two distinct types or classes of pulse jet engines: one of them are known one set of pulsejets are known as valve type pulsejets and the other set of engines are known as valve less pulsejets.

So, we will discuss little bit about both of these types of pulse jets. In fact, little more of the valve less pulsejets because you have already seen valved pulsejets in some detail in the last two lectures. So, in a valved pulsejet engine we use a series of valves which open and close depending upon the operating condition that is as combustion is initiated due to the pressure developed within the combustion chamber the valves upstream of the combustion chamber close and the combustion products are forced to move through the tail pipe and this results in a thrust.

So, as the engine generates thrust the valves again are forced to open because it will also draw in air from the ambient and then again we initiate or ignite or inject fuel in the combustion chamber and that again leads to combustion and the valves close and combustion products are exhausted through the tail pipe and this continues. So, you can immediately see that the thrust generated in a valved or. In fact, in pulsejets are off pulsating or oscillating nature they do not generate a continuous thrust. So, that is one disadvantage of pulsejet in the fact that they cannot generate continues thrust.

So, the in a valved pulse jet one would use mechanical valves sometimes they are referred to as read valves and. So, on these are valves which are one way valves basically which will prevent the flow from the combustion chamber to move upstream it will ensure that the flow always moves only downstream and depending upon the cycle operation if it is combustion phase the valves are closed resulting in combustion products being exhausted through the tail pipe after exhaust process is over the valves open, because there is a partial vacuum created in the combustion chamber which forces the valve open and sucks in air from the ambient and then this cycle is repeated.

So, in a valved combust, on chamber or a valve type pulse jet use of mechanical valves is or the presence of mechanical valves is significant and that is what ensures a the operation of the pulsejet as such.

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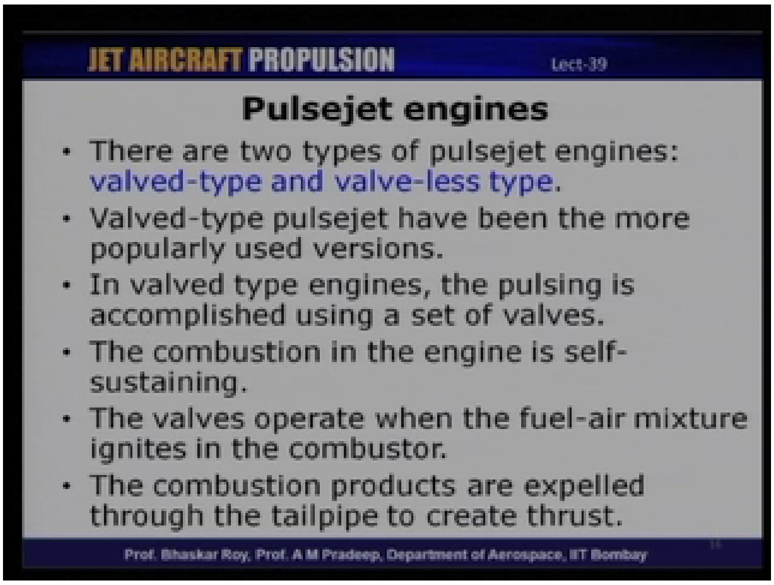

So, in the case of valved engines. In fact, that is true for valve less as well the combustion process is basically self sustaining like any other jet engine one would not have to ignite the fuel all over again every time. So, once you ignite it and the engine starts then the combustion is basically self sustained and the valves basically operate when the combustion initiates in the combustion chamber the valves close and the combustion products are expelled or expel through the tail pipe to create thrust.

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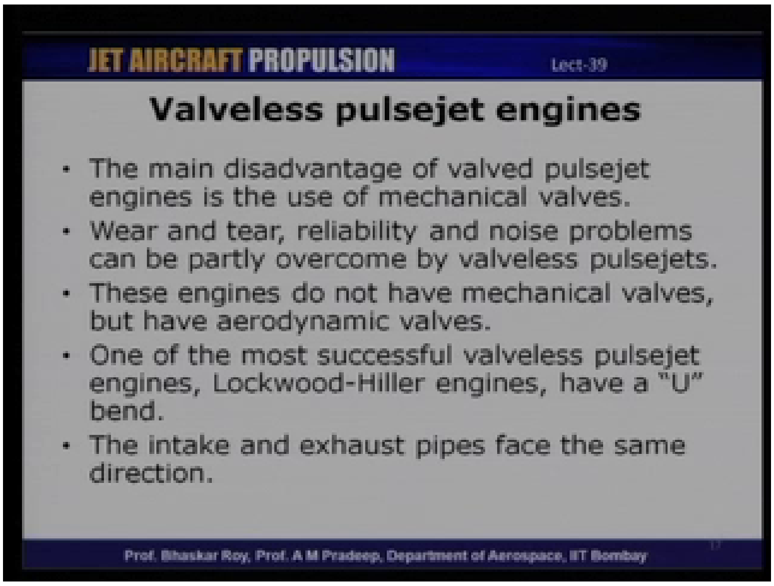

So, this is a valved type of a combustion pulsejet, but there is a big disadvantage for valve type of combustion valve type of pulsejet the major disadvantage being the fact that presence of these mechanical valves means that the there are lot of possibilities of ware and tare and which indeed happens that valve type of combustion pulsejet do not really have a large life. In the sense that they can operate for about thirty minute, so, beyond which the valves of or the mechanical valves will wear out and their operation becomes extremely inefficient. So, that is one major disadvantage of a valve type of a pulsejet the presence of mechanical valves.

So, this can be overcome by avoiding the use of mechanical valves all together, but then how do you create pulsing effect and generate thrust. So, this can be accomplished by using motor known as valve less pulsejet engines which use aerodynamic valves they will not really have mechanical valves, but they have aerodynamic valves. So, in a valve less pulsejet engine the major disadvantage being the presence of mechanical valves there are of course, wear and tear reliability issues and of course, noise problem which can be partly overcome by using valve less pulsejet. So, valve less pulsejets do not have mechanical valves, but they have aerodynamic valves.

Now, the problem of noise is still continuing even in a valve less pulsejet one would still have a lot of noise to deal with but the issue of wear and tear and reliability is much better in valve less pulsejet as compared to a the valve type of a pulsejets, which is why valve less pulsejets also have been explode some of them have actually been used and flown at least to demonstrate the concept. So, one of the most popular forms of valves pulsejet engines which have been demonstrated.

In fact, one of the aircraft actually flew at least the test aircraft flew with a valve less pulsejet to demonstrate the concept. So, the one which has been most popular is known as the Lockwood Hiller design, because they were the inventors of the valve less this particular design of valve less pulse jet. This basically has a u bend that is the exhaust has after the combustion chamber there is a long u bend. In fact, the intake and the exhaust face each other that is they face the same direction and since we are using aerodynamic valve here these valves will leak there will be a certain amount of leakage associated with the valve ,but that can be minimized to generate a net thrust forward.

So, both the intake and exhaust pipe will save for face the same direction and that is the whole concept of using u bend which will cause certain blockage to mimic that of a valve a; mechanical valve. So, using these bend that bend are going to see in the next slide.

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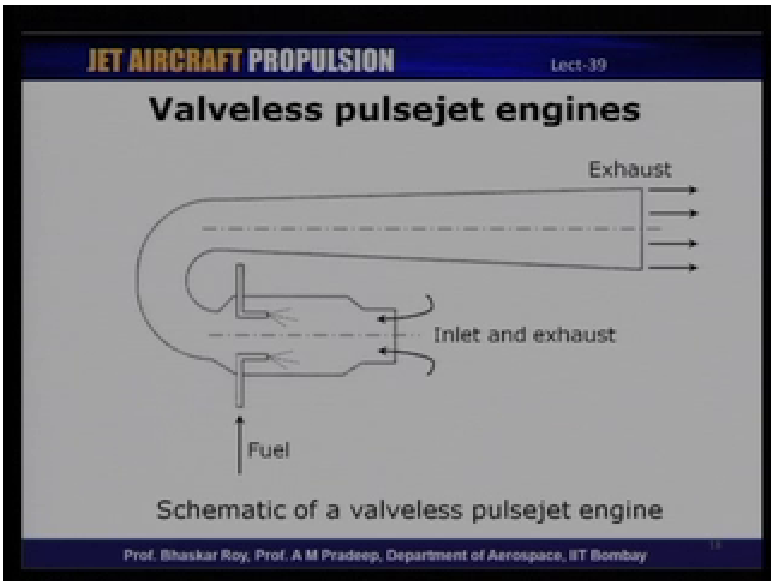

So, in this particular design that you can see this is a schematic of a typical valve less pulsejet engine. So, fuel is initiated or ignited or injected here, this is the intake of the pulsejet engine. So, the combustion the air is drawn into the pulsejet fuel is injected here and ignited. Once ignited the combustion products will be expelled through the exhaust you can see that there is the length of these two are differential. So, combustion products are expelled or exhausted through this some amount of these combustion products also get exhausted through this, but that is very minimal. So, majority of the exhaust goes through this exhaust which is shown here. This results in a net forward thrust. So, this is one of the designs of a valve less pulsejet engine and there are many other designs if you search in the net you will find numerous designs for valve less pulsejet engine this is the one which have been most popular and successful.

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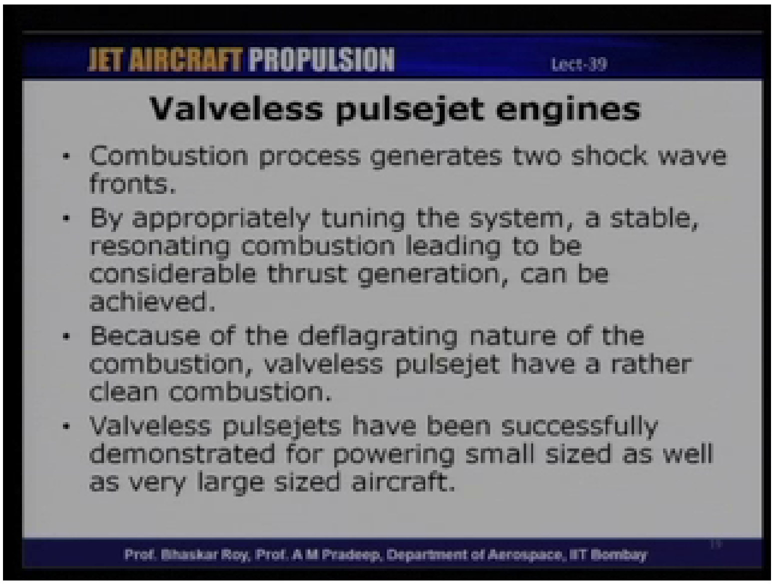

So, in this combustion product process it generates to shock waves and by appropriately tuning the system adjusting the length of the system, one can achieve a stable resonating combustion which leads to considerable thrust generation.

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So, one can tune the length of these two different sections the length of this exhaust pipe and the inlet to ensure that one can achieve a stable resonating combustion which leads to lot of a considerable thrust.

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Now, here the combustion products are combustion process is deflagrating and as a result of these valve less pulsejet engine have a clean combustion that is more or less complete combustion occurs in the valve less pulsejets. They have not been used in actual aircraft; they have been demonstrated, but they have been demonstrated successfully for a range of an aircraft from very small size to very large sizes.

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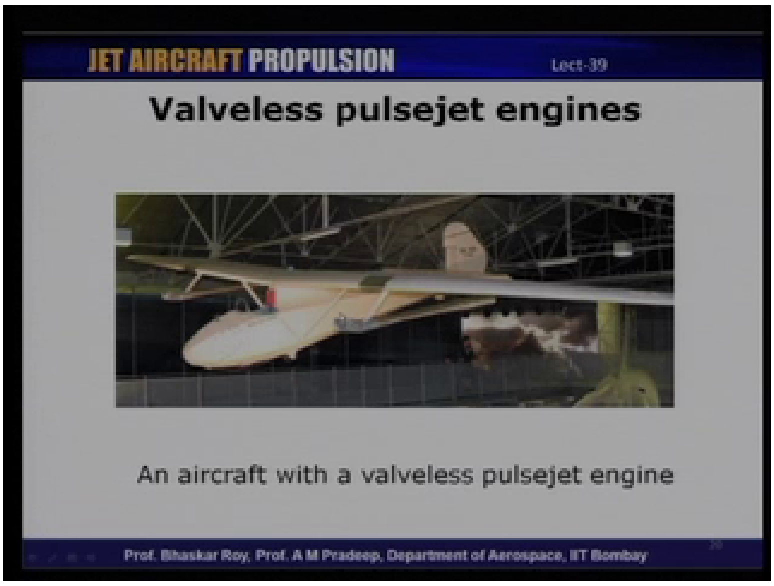

So, this is one example one picture of an aircraft a French aircraft, which has actually got a Lockwood Hiller type of a valve less pulsejet. You can see the engine here this is the valve less pulsejet engine where you can see the u bend and the long exhaust pipe. So, valve less pulsejet engines are characterized by a rather long exhaust pipes you can see the long exhaust pipe here. So, this is one example of an aircraft, which had valve less pulsejet engine.

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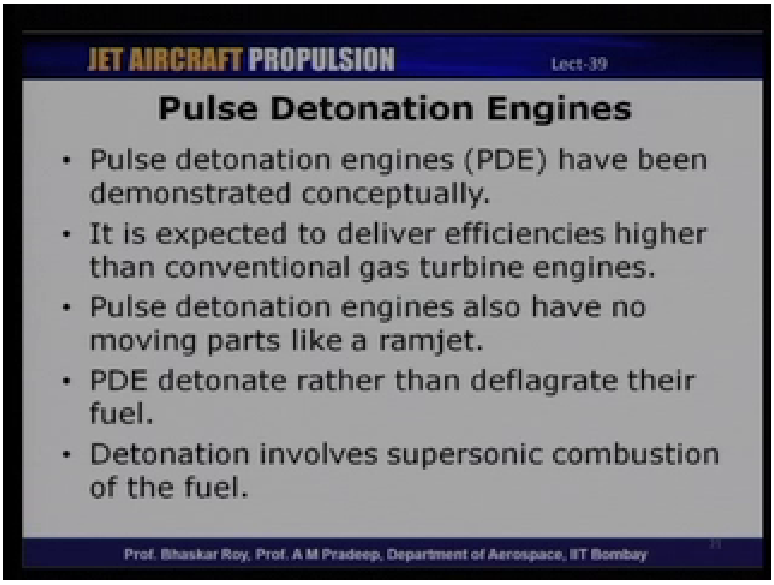

Now, there is another concept, which is also gaining a lot of significance that is known as the pulse detonation engine. They are expected to have efficiencies much higher than conventional gas turbine engines; these engines also do not have any moving parts like a ramjet or a pulsejet and pulsejet detonation engines. Actually, have a detonation rather than deflagration detonation involves supersonic combustion of the fuel unlike deflagration, which is subsonic combustion. Pulse detonation engine as the name itself suggest has detonation, which means fuel ignites at supersonic speeds. So, they are basically been envisaged to be used in supersonic flights unlike the valve less pulsejet engines which are meant for subsonic speeds.

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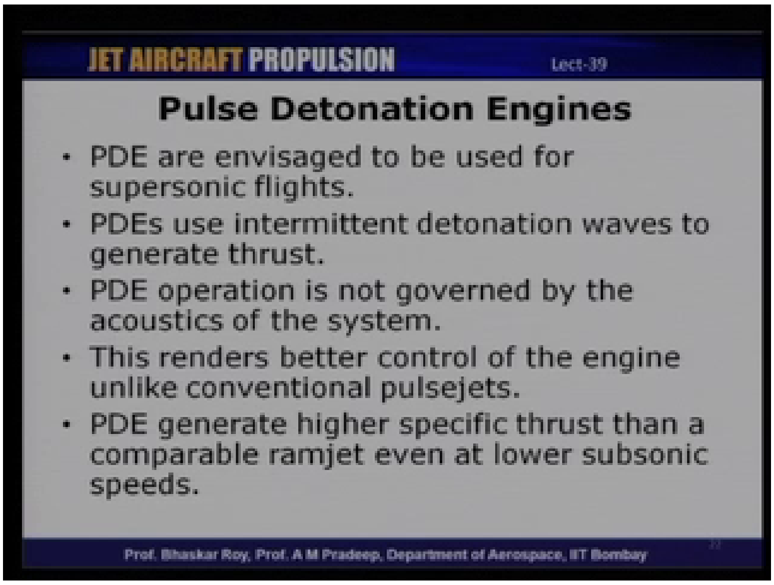

Now, in this pulse detonation engine one would use intermediated detonation waves to generate thrust and the main advantage of the P D E is that they are not governed by acoustics of the system, unlike valve less pulsejet engines or the valves pulsejet engines which means the; that means, they are not governed by acoustics the there is a better control of the engine unlike the conventional pulsejet engines and P D E is generate much higher thrust, which are for a comparable ramjet even at subsonic speeds unlike ramjets which cannot really generate too much thrust at subsonic speeds pulse detonation engines can generate substantial thrust for a comparable ramjet even at subsonic speeds. So, that is very significant advantage of pulse detonation engine.

So, there are different modes of operation of pulse detonation engine like it can be used as a either a standard loan engine where is where in we have just a series of these tubes which constitute the P D E and then all of them generate operate simultaneously to generate thrust or you can integrate with other cycles you can have a combines cycle or you can have a hybrid cycle.

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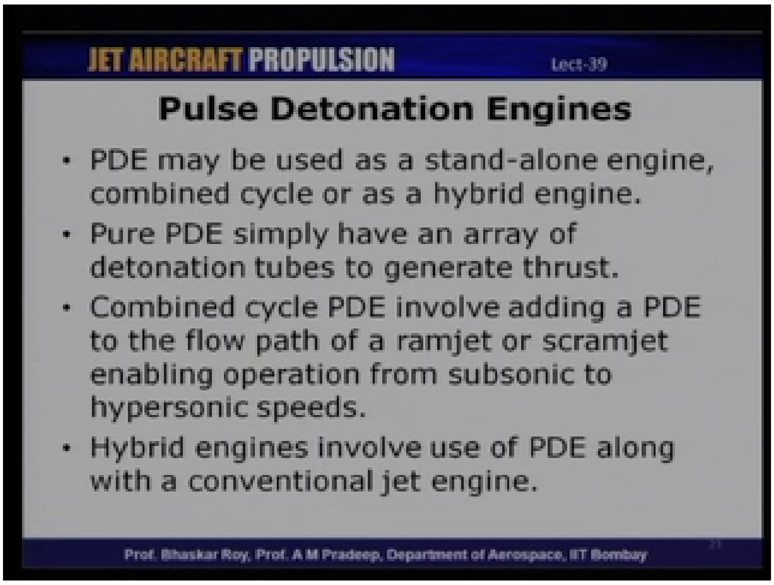

In combine cycle one would add like to add a P D E pulse detonation engine to flow path of a ramjet or a scramjet and therefore, it enables operation even at subsonic speeds and also at high per sonic speed. A combined cycle P D E can actually enable operation of an engine from all the way; from subsonic to high per sonic speed and the third type of PDE are known as hybrid engines. Hybrid engines would involve use of P DE along with a conventional jet engine like a turbofan or a turbojet. Typically a turbofan where one would like to place the P D in the bypass duct and in addition to the core duct, which is like the normal engine we can place the pulse detonation engines in the bypass duct a few of them annular. In the annular occasion, they also generate additional thrust.

So, of course, these are also concept at the movement they are conceptual and may be in the future one might see some of these engines being used in operation and since they are at least theoretically suppose to have much higher efficiencies then conventional engines, it makes a lot of sense to try and explore the possibility of using pulse detonation engine for a aerospace propulsion. So, that was very quick over view of different types of pulse jets valve type, valve less types and the pulse detonation engine let me recap what we discussed.

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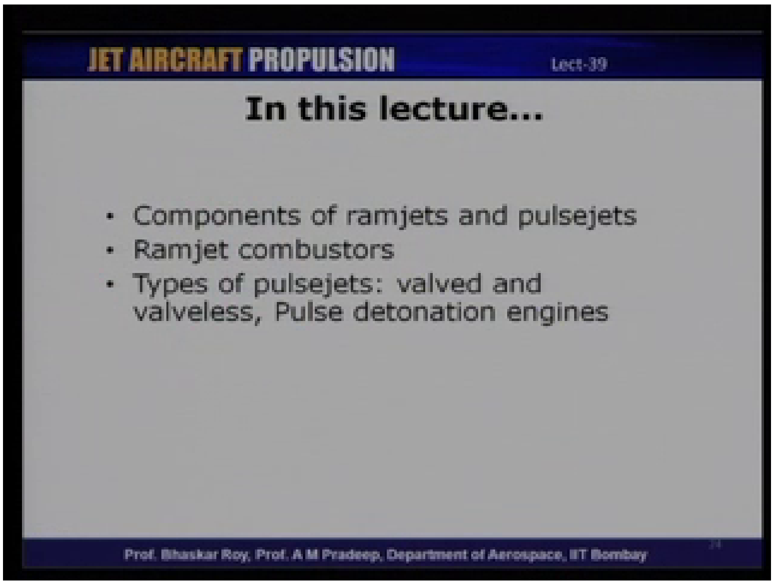

In today's lecture we started off our lecture with discussion on ramjets, we had quite some discussion on ramjets basically focusing on the combustion chamber of a ramjet, because we have already discussed intakes and nozzles in lot more detail earlier. On ramjet combustors were discussed in rather great detail subsequently we discussed about the pulsejets different types of pulsejets the valve type the valve less type of pulsejet and towards the end we also discussed about the pulse detonation engine.

So, with this I would like to wind up this lecture; where we had been discussing about valve ramjet engines types of ramjets and the combustion chamber of a ramjet in detail and types of pulse jets and the pulse detonation engine. So, we would be winding up our lecture series in the next lecture where we will we will also be talking about some of the future concepts of aircraft propulsion and other emerging concepts, which we may see in operation a few years from now. So, that brings us to the end of this particular lecture, which was lecture number thirty nine.